

# Effect of divertor plasma conditions and drifts on ELM power fluxes at the ITER divertor targets

M. Hosokawa<sup>1</sup>, A. Loarte<sup>1</sup>, G.T.A. Huijsmans<sup>2</sup>, T. Takizuka<sup>3</sup>, N. Hayashi<sup>4</sup>

<sup>1</sup>*ITER Organisation, Route de Vinon sur Verdon, 13067 St Paul Lez Durance Cedex, France*

<sup>2</sup>*CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*

<sup>3</sup>*Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan*

<sup>4</sup>*National Institutes for Quantum and Radiological Science and Technology, Naka, Ibaraki 311-0193*

## 1. Introduction

Particle and energy fluxes to the plasma facing components (PFCs) during edge localized modes (ELMs) are expected to unacceptably shorten the lifetime of PFCs in ITER [1]. In order to understand the consequences of kinetic effects on the power and particle fluxes to PFCs by ELMs, PARASOL [2] simulations have been carried out. Initial 1-D simulations showed that both the in/out asymmetry of divertor plasma parameters before the ELM as well as the magnitude of the ELM energy loss itself have an influence on the in/out asymmetry of the ELM divertor power/particle fluxes. The total amount of ELM energy deposited on the hotter/lower recycling divertor is found to be larger when thermoelectric current flow is allowed in the simulations, which is contrary to experiment. Not allowing thermoelectric current flow increases ELM energy deposition at the colder/higher recycling divertor but the degree of in/out asymmetry is smaller than in the experiment [3]. Initial PARASOL-2D simulations were carried out for low recycling divertor conditions to study the effects of plasma drifts on the in/out asymmetry of ELM divertor power and particle fluxes and showed that for the favourable  $\nabla B$  direction the ELM energy flux is predominantly deposited at the inner divertor while for the unfavourable  $\nabla B$  direction this was reversed; this is in qualitative agreement with experiments [4]. In this paper we report on a systematic study of divertor power and particle fluxes in/out asymmetries with PARASOL-2D for stationary conditions and during ELMs including both the effects of divertor recycling and drifts.

## 2. Simulation Models and Parameters

The tokamak plasma is simulated in a cylindrical coordinate system  $(r, \theta, z)$  inside a rectangular region in the  $r$ - $z$  plane surrounded by rectangular walls,  $-a_w < r - R_0 < a_w$  and  $-b_w < z < b_w$ , where  $R_0$  is the major radius of the vessel centre. A regular rectangular grid is adopted for the PIC modelling and axisymmetry is assumed. The magnetic field for the poloidally diverted configurations considered  $\mathbf{B} = (B_r, B_\theta, B_z)$  is produced by the combination of a core plasma current channel and two divertor coil currents. The plasma minor radius  $a$  is defined at the midplane separatrix, and the aspect ratio is given as  $A \equiv R_0/a$ . The toroidal magnetic field  $B_\theta$  is proportional to  $1/R$ , and the pitch of magnetic field  $\Theta \equiv |B_z/B_\theta|$  is provided at the outer mid-plane separatrix as input parameter. The orbits of ions are fully

traced and solved with the leap-frog method, while guiding-centre orbits are followed for electrons by using the predictor-corrector method. The rectangular wall boundary is considered to be electrically conductive, and the wall potential is set  $\phi = 0$ . A source of hot particles is injected in the core plasma to simulate plasma heating. In this study, a uniform source of hot particles (ions and electrons  $T_{i0} = T_{e0} = T_0$ ) is considered for the core plasma region inside the magnetic separatrix ( $-a < r < a$  at the midplane). The number of ions in the simulations  $N_i$  is  $2 \times 10^7$  and the number of spatial cells is  $M_R \times M_Z$  is  $640 \times 1024$ . The size of each cell is 0.25 both for  $r$  and  $z$  direction and the normalized length is determined as  $\Delta l = \Delta t * v_{th,e}$ , where  $\Delta t$  is the normalized time-step and  $v_{th,e}$  is the electron thermal velocity. The mass ratio  $m_i/m_e$  is chosen as 400 to save computation time. In these simulations  $A = 3.1$  and  $\Theta = 0.25$ , which are typical values for ITER (parallel connection length  $L \sim 2\pi a/\Theta$ ). The typical ratio of the ion Larmor radius to plasma minor radius in these simulations is  $\rho_{i0}/a = 0.02$ . The parameter range spanned in the simulations of stationary plasma conditions and during ELMs is summarized in Table 1.

The anomalous transport is simulated with a Monte-Carlo random-walk model. A spatial displacement perpendicular to  $\mathbf{B}$ ,  $\Delta\mathbf{r}_{anom}$ , is added for every time step in the motion equations both on electrons and ions. The isotropic displacement is given by a Gaussian random number  $g$ , and its mean square is

$$\langle \Delta\mathbf{r}_{anom}^2 \rangle = D_{anom} \Delta t \quad (1)$$

$$\delta\mathbf{v}_\perp = \Delta\mathbf{r}_{anom} \Delta t = \sqrt{\frac{D_{anom}}{\Delta t}} g \quad (2)$$

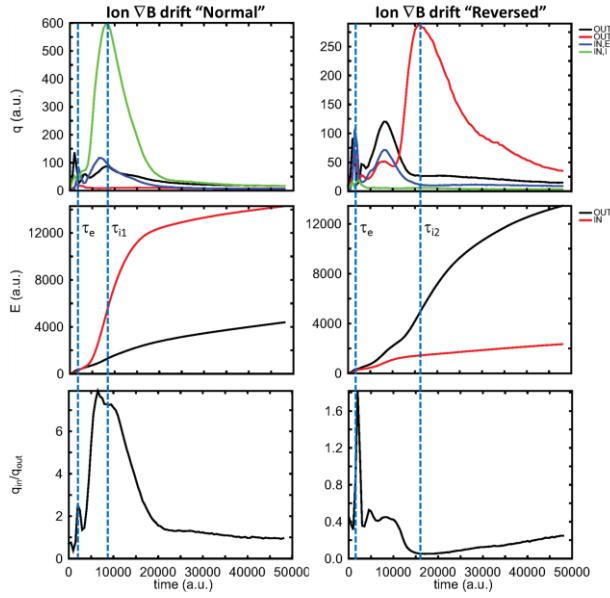
The ELM model in this study is implemented by multiplying Eq. (2) by a constant  $k_{ELM}$  in a selected region of the plasma ( $0.6 < r/a < 1.1$  and poloidal angle extent of  $\Delta\alpha = \pm 60^\circ$ ) and added as an additional displacement caused by the ELM to both electrons and ions to simulate the expulsion of particles by the ELM.

**Table. 1** Modelling parameters for PARASOL 2D simulations between ELMs and at the ELMs.

Collisionality $L_z/\lambda_{mfp}$	0.53, 5.3
ELM duration $\tau_{ELM}/\tau_{\parallel,i}$	$2.6 \times 10^{-2}, 1.3 \times 10^{-2}, 6.5 \times 10^{-3}, 3.3 \times 10^{-3}$
ELM energy loss $\Delta W_{ELM}/W$	12%, 9%, 5.5%, 3%
Recycling ratio $R_{rec}(R_{in}/R_{out})$	0.9/0.9, 0.5/0.5, 0.3/0.3, 0.9/0.5

### 3. Simulation Results

Fig. 1 shows the time evolution of the heat flux  $q$ , total energy deposition at the inner and outer divertors  $E$  and energy deposition asymmetry  $E_{in}/E_{out}$  for a Type I ELM ( $\Delta W_{ELM}/W \sim 12\%$ ,  $\tau_{ELM}/\tau_{\parallel,i} = 0.026$ ) with “reversed” and “normal” ion  $\nabla B$  drift directions. The plasma conditions before the ELM correspond to that of low collisionality  $L_z/\lambda_{mfp} = 0.53$  with symmetric high recycling divertors ( $R_{in}/R_{out} = 0.9/0.9$ ) for both ion  $\nabla B$  drift directions.



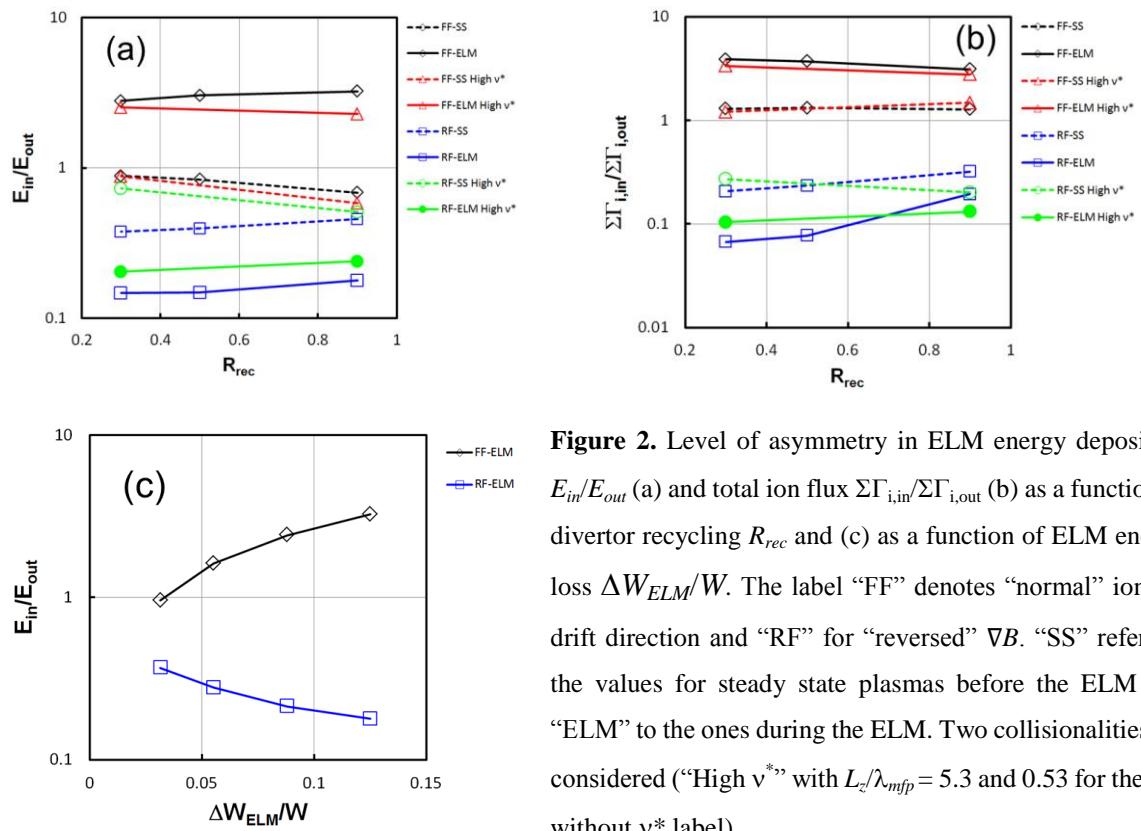
**Figure 1.** Time evolution of ELM heat flux, total energy load to the two divertors and energy load asymmetry for a Type I ELM ( $\Delta W_{ELM}/W \sim 12\%$ ,  $\tau_{ELM}/\tau_{l,i} = 0.026$ ) with high recycling divertors  $R_{in}/R_{out} = 0.9/0.9$  and low collisionality  $L_z/\lambda_{mfp} = 0.53$  for “reversed” and “normal” ion  $\nabla B$  drift directions. The label “OUT” refers to the outer divertor, “IN” to the inner divertor, “E” to the electron and “I” to the ion channels.  $\tau_e$  is the time when electron heat flux at the inner target is maximum.  $\tau_{i1}$  corresponds to the maximum heat flux at the outer divertor for “reversed”  $\nabla B$  and  $\tau_{i2}$  to the maximum heat flux at the inner divertor for “normal”  $\nabla B$  case.

A systematic study has been carried out to identify the effect of various SOL/divertor conditions and ELM energy loss magnitude on ELM divertor heat and particle fluxes and on their asymmetries together with the effect of drifts. The results are summarized in Figs. 2 (a) and 2(b) for the ELM energy load and total particle flow asymmetry, where dashed lines correspond to steady state pre-ELM plasma conditions (“SS”) and solid lines correspond to the ELMs; both “reversed” and “normal” ion  $\nabla B$  drift direction are shown (Type I ELMs with  $\Delta W_{ELM}/W \sim 12\%$ ,  $\tau_{ELM}/\tau_{l,i} = 0.026$  and  $L_z/\lambda_{mfp} = 0.53/5.3$ , with 5.3 corresponding to “High  $v^*$ ”). Fig. 2 (a) shows that higher recycling rates increase the energy load asymmetry between ELMs (SS) for “normal”  $\nabla B$ , while for “reversed”  $\nabla B$  the asymmetry dependence on recycling rate changes with edge collisionality. The higher divertor energy load asymmetry with “reversed” vs. “normal”  $\nabla B$  in SS is contrary to experiment; this is due to a large change of the ion flux asymmetry with  $\nabla B$  direction which is overestimated by our PIC model compared to the experiment (Fig. 2(b)). On the other hand, our simulations show that  $E_{in}/E_{out} \gg 1$  for “normal”  $\nabla B$  while  $E_{in}/E_{out} \ll 1$  for “reversed”  $\nabla B$ , independent of divertor recycling rates. This is in qualitative agreement with experiment, although our simulations overestimate the  $\nabla B$  effects compared to experiment. It should be noted that the magnitude of  $\Delta W_{ELM}/W$  also affects the in/out ELM energy deposition asymmetry so that the results of Figs. 2(a) and (b) are only valid for  $\Delta W_{ELM}/W \sim 12\%$ . In fact, at low collisionality  $E_{in}/E_{out}$  increases with  $\Delta W_{ELM}/W$  for “normal”  $\nabla B$  while it decreases with “reversed”  $\nabla B$  (see Fig. 2 (c)).

#### 4. Summary

The effect of divertor recycling, in/out recycling asymmetries and ion  $\nabla B$  drift direction on in/out divertor power and particle flux asymmetries for stationary plasma conditions and during ELMs have been modelled with the 2-D PARASOL PIC kinetic code. The direction of the ion  $\nabla B$  drift has a strong effect on the steady-state in/out heat/particle flux divertor

asymmetries and this effect is even larger for ELMs. The modelled changes of the in/out divertor asymmetries with  $\nabla B$  for steady state conditions are contrary to experimental findings (the inner divertor heat flux does not become similar to outer one when  $\nabla B$  direction is reversed). Simulations of ELMs find that the energy load to the inner divertor is largest for normal  $\nabla B$  and smallest for reversed  $\nabla B$  for an ELM energy loss of  $\Delta W_{ELM}/W \sim 12\%$ . This finding is robust to modelling assumptions (recycling value, in/out recycling ratio, ELM energy loss magnitude and plasma collisionality). This is good qualitative agreement with experiment, although magnitude of the predicted changes is much larger than in experiment. The magnitude of  $\Delta W_{ELM}/W$  itself is also found to affect the in/out ELM energy deposition asymmetry and  $E_{in}/E_{out}$  increases with  $\Delta W_{ELM}/W$  for “normal”  $\nabla B$  while it decreases with “reversed”  $\nabla B$  for low collisionalities. Further 2-D PARASOL simulations to study the role of drifts, recycling and thermoelectric currents are in progress to refine these findings.



**Figure 2.** Level of asymmetry in ELM energy deposition  $E_{in}/E_{out}$  (a) and total ion flux  $\sum \Gamma_{i,in}/\sum \Gamma_{i,out}$  (b) as a function of divertor recycling  $R_{rec}$  and (c) as a function of ELM energy loss  $\Delta W_{ELM}/W$ . The label “FF” denotes “normal” ion  $\nabla B$  drift direction and “RF” for “reversed”  $\nabla B$ . “SS” refers to the values for steady state plasmas before the ELM and “ELM” to the ones during the ELM. Two collisionalities are considered (“High  $v^*$ ” with  $L_z/\lambda_{mfp} = 5.3$  and 0.53 for the one without  $v^*$  label).

*Disclaimer: ITER is the Nuclear Facility INB no. 174. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.*

## 5. References

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